WATER–ENERGY–FOOD NEXUS TOOL SELECTION AND APPLICATION OF TOOLS TO A REGIONAL CASE STUDY

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ABSTRACT

Energy, as an integral resource to everyday life, cannot be separated from the other resources involved in its extraction, production, and consumption. The water–energy–food nexus (WEFN) conceptualizes resource sustainability because it frames the interlinkages across sectors, accounting for resource flow across systems. Thus, future sustainable energy resource planning goes hand in hand with overall resource and environmental sustainability. This entails that systems be considered holistically, especially in the planning and production stages, and this can be achieved by applying tools that address the integrated WEFN. While the literature supports a growing number of these tools, the breadth of WEFN applications renders it difficult to determine which tools are suitable for different objectives and users. This work provides a systematic selection approach that applies multi-criteria decision making to determine which tool best fits a set of circumstances. The selection criteria are developed to reflect tool features as comprehensively as possible, accounting for: economic, social, and environmental factors, temporal/spatial scales, stakeholder inclusion, parameter comprehensiveness, and tool complexity, flexibility, and accessibility. Three unique user (scientific user, policymaker, and non-technical stakeholder) scenarios are simulated via distinctive weighting schemes. Of an initial pool of 40 tools, four tools are selected across varied user scenarios. The selected tools are applied to a case study to better demonstrate how the tools differ in performance, as is appropriate for respective user objectives. Case study applications indicate that results are sensitive to assumptions and input data, and that the nature of results across tools differ significantly. The work is versatile in that selection criteria and weighting schemes can be more specifically tailored to cater to specific user needs. Once the WEFN approach is integrated into energy management, the overall perspective on sustainability will improve as advancement in one aspect does not come at the expense of another.

Keywords: water–energy–food nexus, multi-criteria decision making, analytical hierarchy process, resource management, tools, selection, sustainability.

1 INTRODUCTION

With the projected increase of the global population to reach 9.8 billion by 2050, the corresponding increase in resource demand is 55% for water, 60% for food, and 50% for energy [1]–[3]. However, reducing the global demand for a specific resource is not a problem that can be addressed in silo, as this reduction may come at the expense of another resource, possibly exacerbating the problem overall [4]. This is due to the interconnected nature of resources, where water is needed for energy production, energy is needed for water treatment, and both energy and water are needed for food production. The water–energy–food nexus (WEFN) is a concept that accounts for the interlinkages of these resources and thus provides a context for problem solving more sustainably, especially as relates to resource management [5].

The general scientific consensus is that energy consumption has come to be a critical environmental problem that must be addressed. This is because energy is directly related to economic growth, in turn accounting for 87% for global greenhouse gas (GHG) emissions [6]. The situation is especially challenging because, even at this rate of consumption, there

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remains 1.2 billion people without access to electricity [7], meaning that as living conditions improve, it is expected that GHG emissions will also increase.

To address this problem, it is imperative that energy problems be considered in a WEFN context to prevent the transfer of problems from one resource sector to another and improve overall sustainability [4]. Furthermore, a WEFN framework allows for the incorporation of related challenges (urbanization and economic growth) for more inclusive solutions [8]. An intermediary solution is to leverage existing WEFN tools that cater to sustainable resource allocation and management.

However, while there is a growing number of WEFN tools, little work addresses the selection of a suitable tool for an intended use. While Rosales-Asensio et al. [9] put forth a WEFN decision making framework targeting energy management, they do not apply the suggested criteria to select a tool. Dargin et al. [10] propose a complexity index, developed from eight criteria, to determine the "usability" of eight WEFN tools. Schull et al. [11] apply multi-criteria decision analysis to select a WEFN tool from a total of seven tools using qualitative criteria. In these works, limited tools and criteria are used.

This work puts forth a more involved selection approach, with a versatile nature that allows for its replication with more specific aims in mind. The objectives of this work are: (i) to identify which tools are suitable for differing user needs; (ii) to compare the performance of the selected tools; and (iii) to provide recommendations for further tool improvement. This is accomplished by using multi-criteria decision making (MCDM) to determine which tools best assess the WEFN across different scenarios and applying the selected tools to a specified case study to examine their performance.

2 METHODOLOGY

The applied approach consists of two sections. The first pertains to the WEFN tool selection, and the second applies the selected tools to a case study for further analysis.

2.1 WEFN tool selection

MCDM is applied for the selection approach, because the use of multiple criteria allows for more inclusive assessment of measures that would not be typically included within a single scientific method (due to inability to directly compare these criteria) [12]. In addition, the use of multiple criteria has the capability of addressing diverging goals at the same time [13]. Decision maker preference guides the process to ensure that the most suitable choice is selected [14]. The tool selection approach consists of: (i) identifying the initial set of suitable tools; (ii) specifying the assessment criteria; (iii) rating the tools according to the criteria, iv) generating criteria weights for designated user scenarios; and (iv) applying MCDM to select the tools.

2.1.1 Initial set of WEFN tools

The first step of the selection process is determining the initial set of WEFN tools. These tools are extracted from the literature by applying three filter criteria: (i) a tool must include all three sectors of the WEFN; (ii) the tool must be available; and (iii) tool must be applicable to a case study. Scopus (scientific database), the Nexus Resource Platform website (https://www.water-energy-food.org/), and literature reviews addressing nexus tools [15]–[18] were studied to identify potential tools. Based on these resources and in accordance with the filter criteria, a total of 40 tools are initially selected (as of December 2020).

2.1.2 Criteria development

A set of ten criteria is developed to cover WEFN tool characterization, based on a study of the WEFN and MCDM literature [7], [13], [16], [18]–[22]. The criteria span different aspects of tool use and endeavour to account for generic considerations that are made when selecting tool, going beyond the scientific aspects. The criteria catering to the scientific aspects of tool use are: *factors* (referring to the number of economic, environmental, and social factors included in the tool), *parameter comprehensiveness* (i.e. the number of parameters capturing nexus interlinkages), *scenario building* (reflecting tool's capacity for additional sensitivity analyses and scenario changes), *spatial scales* (how applicable the tool is across areas: local/ national/regional/global), *temporal scales* (whether the tool includes time-related considerations in its analyses), and *uncertainty* (if the tool accounts for risk and associated uncertainty). The non-scientific criteria are: *availability* (how easily a user can access the tool), *model complexity* (as a proxy for tool's ease of use), *flexibility* (how easy it is to adapt the tool to other case studies), and *stakeholder inclusion* (to assess how well the tool caters to other related parties).

The tools are assessed based on how well they rate with respect to these criteria. The rating is based on a rubric that defines scores numerically and qualitatively for maximal transparency. The rubric is defined such that each criterion has up to five levels corresponding to a specific numerical score (ranging from 1 to 9, the latter being the most preferred). For example, if a tool can only be applied to one specific city, it is assigned a score of 1; whereas, if it can be applied across multiple (two or more) spatial scales, it is assigned a score of 9. The same concept is applied to all criteria, noting that other criteria might have more than two levels. The factors criterion is a special case, such that the score is the average of scores for each of economic, environmental, and social factors separately, such that the scores are: 1 if no factors are included, 3 if one factor is included, 5 if two factors are included, 7 if three factors are included, and 9 if more than three factors are included. The scores for each factor type (economic, environmental, and social) are averaged for a final score for the factors criterion.

2.1.3 Criteria weighting

Three alternative weighting schemes, in addition to an equal weighting scenario, are applied to model tool selection for three different users: (i) scientific user; (ii) policymaker; and (iii) non-technical stakeholder. Weights are generated to reflect diverse user preferences, which may render a different tool more suitable for each scenario. The SMARTER (Simple Multi-Attribute Rating Technique Exploiting Ranks) method is used to determine criteria weights. SMARTER operates based on order of importance ranking, where the decision maker ranks the criteria set in order of consecutive importance, and this order is converted into a set of weights using the rank order centroid [23], using Logical Decisions v7.2 software.

2.1.4 Decision matrix

Logical Decisions v7.2 software is also used for the selection analysis, requiring the input of the decision matrix. The decision matrix is compiled from: (i) WEFN tools as alternatives; (ii) developed criteria as assessment measures; and (iii) the tool scores; and (iv) the criteria weights for each user scenario. The overall performance of an alternative is calculated with a linear additive model that sums the product of each criterion weight and corresponding rating.

2.2 Case study on selected tools

The selected tools comprise those ranking first in each of the scenarios described in the previous section. A case study is applied to each of these tools to analyse how and why results may differ. The objective of the case study is to assess the Lebanese WEFN. As such, a point of reference, resource consumption (for the year 2018), is specified to enable numerical comparison across different tools.

Lebanon is located in the Mediterranean region, with a population of 6.85 million [24]. Lebanon imports over 97% of its energy mostly in the form of petroleum [2]. Approximately 48% of it is used for electricity production (generating approximately 21.24 GWh [2]), the remaining is used for non-energy functions. In terms of water resources, Lebanon primarily relies on surface water and groundwater, consuming approximately 1500 million cubic meters of water [25]. Lebanon's food sector consists of livestock and agricultural crops. For the comparison, tool performance is gauged by how accurate simulated resource (crops, water, and energy) consumption values are compared to actual resource consumption (derived from global and national databases). It is noted that certain assumptions are made with respect to consumption values, as relates to domestic supply, and based on available data.

Fig. 1 summarizes the proposed methodology.

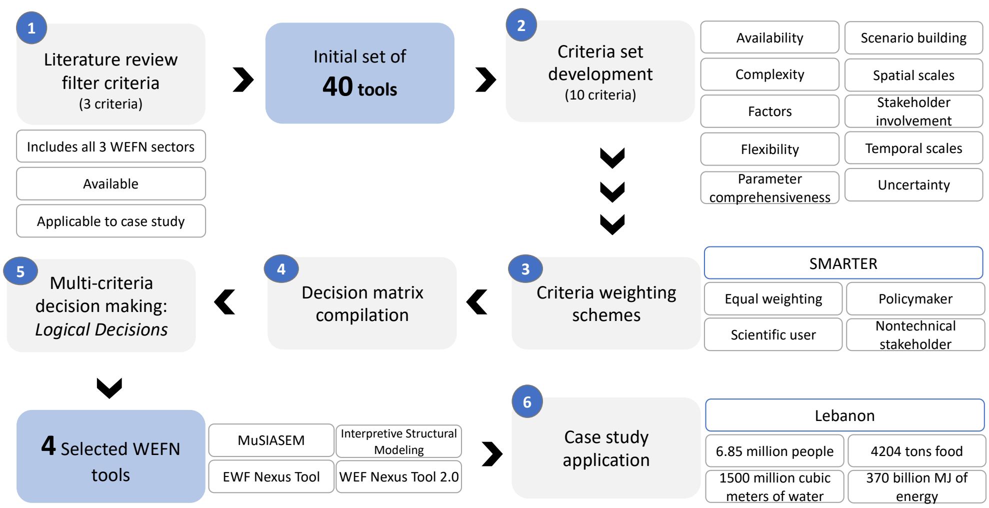

Figure 1: Summary of selection approach methodology.

3 RESULTS

The first set of results pertains to the WEFN tool selection, while the second presents the results of tool application to the described case study.

3.1 WEFN tool selection

The weighting schemes generated for each user scenario are summarized in Table 1. Parameter comprehensiveness and scenario building are the most important criteria for the scientific user scenario. On the other hand, stakeholder inclusion and the factors criteria are

Table 1: Criteria weights for three user scenarios.

Criteria	User weighting schemes		
	Scientific user	Policymaker	Non-technical stakeholder
Availability	0.034	0.048	0.193
Complexity	0.021	0.143	0.293
Factors	0.048	0.193	0.085
Flexibility	0.085	0.034	0.065
Parameter comprehensiveness	0.293	0.085	0.110
Scenario building	0.193	0.110	0.143
Spatial scales	0.065	0.001	0.048
Stakeholder inclusion	0.010	0.293	0.010
Temporal scales	0.110	0.065	0.034
Uncertainty	0.143	0.021	0.021

the more important ones for the policymaker user. Tool complexity and availability are the driving criteria for the non-technical stakeholder.

The tools selected for the designated scenarios are presented in Table 2.

Table 2: Selected tools for baseline and user scenarios.

User scenario	Selected tool	Description of tool
Baseline	MuSIASEM [26]	This tool, Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), applies a resource accounting method that studies metabolic patterns in society. It analyses data at different hierarchal scales allowing for better analysis of nexus synergies (energy, food, and water and their interrelations) and consequent societal impacts.
Scientific user	EWF Nexus Tool [27]	This tool is based on life cycle analysis (LCA) and assesses the performance of WEF systems from the cradle to grave via the quantification of environmental impacts. Each nexus resource has a subsystem, such that transfers between these subsystems represent the nexus interactions
Policy maker	ISM [28]	This tool, Interpretive Structural Modelling (ISM), converts nexus interlinkages and interdependencies into a well-defined model using the concepts of reachability and transitive inference. The tool results in a hierarchy of WEFN factors using feedback and input from a panel of experts/ stakeholders.
Non-technical stakeholder	WEF Nexus Tool 2.0 [29]	This tool uses a scenario-based framework that quantifies flows of matter and energy between nexus dimensions. Input and output vales are then used to compute an overall sustainability index, which is a decision-making indicator for comparison between different scenarios.

The four tools selected across scenarios score highly with respect to the key criteria characterizing each scenario. The MuSIASEM tool is the one chosen for the baseline. Its scoring shows it to be a good tool in terms of covering most criteria bases. The EWF Nexus Tool was selected for the scientific user scenario because it caters to extensive technical modelling with very detailed data requirements and comprehensive accounting for embedded processes. As for the policymaker scenario, the Interpretive Structural Modelling (ISM) tool directly integrates expert/stakeholder dialogues (in the form of surveys or panels), rendering it a suitable choice for this scenario. The WEF Nexus Tool 2.0 is suitable for the nontechnical stakeholder, as it is user friendly and can be used without any prior training.

3.2 Case study on selected tools

To apply to the case study of Lebanon, the required input data is adjusted accordingly for the different tools. Table 3 presents a summary of the resulting WEFN resource consumption across the selected tools, as applicable.

Table 3: Summary of total resource consumption across tools.

Tools	Resources consumed		
	Water (m^3)	Energy (MJ)	Food (10^6 tons)
EWF Nexus Tool	1.45E+08	3.68E+11	2.52
ISM	5.96 E+08	3.70E+11	4.20
MuSIASEM	5.96 E+08	3.70E+11	4.20
WEF Nexus Tool 2.0	0.08 E+03	5.86E+08	–

The application of MuSIASEM entails obtaining the overall resource consumption values from the appropriate databases and breaking down across a specified societal hierarchy (of sectors). On the other hand, ISM does not include direct quantitative values. The tool generates a hierarchy of factors indicating which are most important for the assessed WEFN context. The tabulated values are simply attributed to the consumption factors post-analysis. In other words, water, energy, and food consumption are the factors included in the ISM analysis (and within the generated factor hierarchy), but the values in the table are those obtained from the literature for Lebanon and simply assigned to the considered factors as appropriate for the purpose of numerical comparison. As such, given the more involved nature of the tool, for the objective of this comparison and using existing databases as a reference, MuSIASEM is deemed most accurate in capturing WEFN interactions.

The EWF Nexus Tool results are within the same range of magnitude as those of MuSIASEM. This is also because the EWF Nexus Tool employs researched data values specific to the Lebanese WEFN. The differences between the values generated by these two tools are due to: (i) differing assumptions made based on available data; and (ii) embedded processes within life cycle analysis (LCA) that are not accounted for in MuSIASEM. For example, in the application of the EWF Nexus Tool, only a limited number of crops were included in the simulation and water consumption was limited to irrigation and electricity production. In addition, the LCA simulation of a crop includes fertilizer and pesticide use, which are not typically included in generic consumption values. The ability of these two tools to take on specific context-based values renders them more accurate than the remaining tools.

With respect to the WEF Nexus Tool 2.0, although it does incorporate WEFN resources, results are specific to the food production sector. Accordingly, the water consumed is less than that in MuSIASEM because the water considered in the tool is only that used for specific crop production. On the same note, the energy for food production in the WEF Nexus Tool is lower than the total amount of energy consumed in Lebanon as a whole (before energy sector consumption). The consumed amount is still high considering that only the food production sector is assessed. This can be explained by the tool's inclusion of energy consumption in irrigation, other agriculture-related process, and transport, which are not explicitly included in the other tools and are designed to cater to Qatar's specifications. It is noted that the crops available in the WEF Nexus Tool 2.0 do not capture those that are important to the Lebanese food sector, rendering the results incomplete.

4 DISCUSSION

The first section of discussion addresses the selected tools for the simulated users, the results of the case study, and the recommendations for a "universal" tool. The second section of the discussion examines the versatility of the applied selection approach, focusing on how the approach can be adapted to serve other users and more specific objectives.

Before delving into these discussions, the suggested selection approach is compared to the limited work done around this topic. Rosales-Asensio et al. [9] uses three criteria (two out of three nexus sectors, capability of evaluation at high level, and open accessibility and availability) to determine the initial set of tools to which three examination principles are to be applied: input entry requirements (in terms of data), output expectations (i.e., what inquiries can be answered with the tool), and analytical aspects of the tool. However, tool selection is not effectively applied to showcase the framework's capabilities. In the determination of their complexity index, Dargin et al. [10] use eight criteria (data accessibility, user friendliness, accessibility, data granularity, data requirements, training intensity, subject matter expertise requirement, and user defined scenarios). The computed index is meant to be used as a decision aid for tool comparison and selection with respect to nexus scope and externalities, tool methodologies, and tool purposes. Schull et al. [11] focus on the selection of water management-oriented tools within a nexus context. The initial set of tools was obtained from the literature using an exploratory approach. The criteria applied to the set of tools are: availability and accessibility, user friendliness and simplicity, flexibility, comprehensiveness, and predictive component. An unweighted qualitative decision matrix approach is used to rate the tools for selection.

In this work, the selection approach is meant to identify the suitable WEFN tool for a specific user. Compared to the other selection approaches, this work considers a larger initial pool of tools identified using three distinct filter criteria, permitting a wider range of choice. In addition, a larger number (ten) of evaluation criteria are applied, with detailed descriptions of the criteria and their levels for more specific rating and overall utility calculation. The criteria also span a broader range of tool aspects for more comprehensive tool characterization, both technically (ex. spatial and temporal scales) and beyond the technical (ex. stakeholder inclusion). The approach also ties in user preference with respect to the expected objective behind tool use to guide the selection process by simulating two potential users and correspondingly deriving the appropriate weighting schemes. Furthermore, a comparative analysis is conducted by applying the same case study to the four tools selected across the varying user scenarios, which to the authors' knowledge has not been done before. The application of the same case study to different tools allows for deeper insight to the analytical differences of tools and provides a basis for fit analysis with respect to user needs.

4.1 Selected tools, case study applications, and "universal" tool specifications

More accurate results tend to come at the cost of data extensiveness and time-consuming applications. As such, MuSIASEM tool is relatively effective at characterizing the WEFN due to its detailed (level of detail is user specified) flow of elements within the system, and its relatively straightforward application. It enables the user to identify sources and sinks in the system, thus highlighting sectors of high consumption and determining the level of dependency among resources. The tool is more of an open-ended methodology that can be customized to context specifications. As for the EWF Nexus Tool, aside from the ability to specify production amounts and detailed input factors, the software simulates resource flows across specified processes and includes all embedded processes in the simulation. Additionally, this tool calculates the environmental impacts associated with the simulated processes. However, the EWF Nexus Tool is difficult to use and requires a significant amount of time to learn software application and acquire data.

While the ISM tool does provide a qualitative analysis in terms of factor importance, it does not provide any information about the magnitude of flows between sectors, and consequently cannot effectively model the WEFN. It is useful in that the hierarchical structure can provide direction in terms of what factors and/or sectors should be focused on. However, it is highly subjective to expert judgment in the formation of connections. As for the WEF Nexus Tool 2.0, it has a limited set of options for inputs and outputs, with major assumptions that significantly impact results. As such, it cannot be used for accurate modelling of the WEFN in countries other than Qatar. And even then, the analysis is of a very specific nature, catering to food security with a limited selection of crops included.

It is noted that these results are not intended to fully capture the breadth of utilization for these tools, but to provide insight into the performance of the tool in assessing the WEFN. Each tool has its advantages and disadvantages, and further reinforces the difficulty in capturing the WEFN in its entirety and potentially explains why no there is no "universal" WEFN tool.

Perhaps, an alternative to achieving a "universal" WEFN tool is combining existing tools so that they compensate for what the other lacks. Based on the selected tools in this work, an all-around tool would combine the key contributions from each tool and allow the user to select the level of modelling complexity and system specificity needed. It would: (i) integrate stakeholder involvement (ISM and MuSIASEM); (ii) account for environmental impacts (EWF Nexus Tool); (iii) characterize WEFN resource flows across multiple levels, including climatic zones (MuSIASEM and EWF Nexus Tool); (iv) identify factors of strength and liability (ISM); (v) account for trade flows (WEF Nexus Tool 2.0, MuSIASEM, and EWF Nexus Tool); and (vi) have a user-friendly interface (WEF Nexus Tool 2.0).

4.2 Selection approach versatility

The vastness of the nexus, its many interconnections, and potentially diverging stakeholder interests render it nearly impossible to satisfy all user interests simultaneously, particularly with a single tool. This is beside the conflicting nature of some criteria. For example, it is the general rule that more accurate and comprehensive tools (characterized by high ratings on: *parameter comprehensiveness, spatial scales, temporal scales,* and *uncertainty*) tend to require more data for application and are harder to use (*model complexity* and *availability*). As such, it is worth investigating approaches that cater to the selection of a WEFN tool as suits a particular user.

In the presented approach, the developed selection criteria set spans multiples bases of interest, and then proposes weighting in accordance with user interest. In cases where the user has a very specific objective in mind, more criteria can be added, or existing ones parsed out to better reflect the characteristics the user is looking for in a tool. For example, if a user wants to focus on energy production, a filter criterion can be added where the initial pool of tools consists of those that focus on energy in a WEFN context. With that in hand, more specific criteria can be applied as measures to select the most suitable tool. Building on the previous example, tailoring this approach to energy production, the criteria set can be customized include more technical factors such as: specific energy costs, land requirements for energy technologies, and water requirements for energy production. A rubric can be constructed with levels for each criterion based on number of energy technologies or cost factors included.

As for the weight derivation process, it functions to accommodate user preference so that the selected tool best reflects user interest. With respect to the simulated user scenarios, generic user roles are assumed for demonstrative purposes. They are not meant to capture the depth of these roles. However, they provide an example of how criteria importance differs from one user to another. Adapting criteria weights, whether it be via the same weight generation method or another, allows the user to determine the importance of each criterion as best fits a particular scenario or reflects a user’s background.

This is not to say that a tool will be found to cater to every need. In such a case, an apparent literature gap is highlighted, and further work can be done that basis.

5 CONCLUSION

The WEFN, in its conceptual nature, deals with resource production, management, and allocation under the umbrella of environmental sustainability. Naturally, tools developed in line with this premise will also cater to these issues. However, the breadth of the WEFN in its spanning all three resource sectors, accounting for interlinkages between these sectors, and expanding beyond the scientific domain for effective implementation gives rise to a myriad of tools with dissimilar, albeit WEFN related, objectives. The abundance of nexus tools, with no systematic selection strategy, complicates an intrinsically complicated problem. As no single nexus model can address all WEFN aspects, as of yet [30], moving forward, it may be worth to focus on developing more advanced selection processes so as to provide a systematic means for determining which WEFN tool best applies to a given situation or specified set of user preference.

This work proposes an MCDM selection strategy designed to cater to different user needs (scientific user, policymaker, non-technical stakeholder). The selected tools are MuSIASEM (baseline scenario with equally weighted criteria), EWF Nexus Tool (scientific user scenario), ISM (policymaker user scenario), and the WEF Nexus Tool 2.0 (non-technical stakeholder scenario). The performance of the selected tools varies in accordance with varying user needs. Case study applications of these tools to the Lebanese WEFN show how each tool differs in terms of input, methodology, and output. Beyond the demonstrative scope of this work, it is noted that all tools can be used, with different objectives, for more (or less) detailed analysis, as per the user’s needs.

The presented selection analysis provides a rudimentary rundown of existing WEFN tools for different use scenarios. With the growing number of tools in the literature, the initial set of tools can be further expanded. The tool selection approach caters to environmental sustainability by promoting WEFN tool utilization and ensuring that improvement in one environmental compartment does not come at the expense of another. However, a key feature of this work is its versatility in fitting to more specific environmental objectives such that the specified objective is addressed with a suitable tool in a WEFN context. Tailoring the selection process can come in the form of more specific criteria, a modified scoring rubric, and more particular weighting schemes, all in accordance with the user's objectives. Future improvements to the approach include: (i) incorporation of the growing number of WEFN tools; (ii) more specific tool use objectives so that outputs can be aligned with specific tool uses/expectations/outputs; and (iii) the incorporation of expert opinion to the weight derivation process to better cater to appropriate tool use.

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